

Compact cold atom gravimeter for field applications

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We present a cold atom gravimeter dedicated to field applications. Despite the compactness of our gravimeter, we obtain performances (sensitivity $42 \mu\text{Gal}/\text{Hz}^{1/2}$, accuracy $25 \mu\text{Gal}$) close to the best gravimeters. We report gravity measurements in an elevator which led us to the determination of the Earth's gravity gradient with a precision of 4 E. These measurements in a non-laboratory environment demonstrate that our technology of gravimeter is enough compact, reliable and robust for field applications. Finally, we report gravity measurements in a moving elevator which open the way to absolute gravity measurements in an aircraft or a boat.

Cold atom interferometer is a promising technology to obtain a highly sensitive and accurate absolute gravimeter. Laboratory instruments [1–3] have already reached the performances of the best classical absolute gravimeters [4] with a sensitivity of $\sim 10 \mu\text{Gal}/\text{Hz}^{1/2}$ ($1 \mu\text{Gal} = 10^{-8} \text{m/s}^2$) and an accuracy of $5 \mu\text{Gal}$. Moreover, compared to classical absolute gravimeters, atom gravimeters can achieve higher repetition rate [5] and do not have movable mechanical parts. These qualities make cold atom gravimeters more adapted to onboard applications like gravity measurements in a boat or in a plane. Cold atom gravimeters could thus be very useful in geophysics [6] or navigation [7]. In this context, cold atom sensors start to be tested on mobile platforms. An atom accelerometer has been operated in a 0 g plane [8]. An atom gradiometer has also been tested in a slow moving truck [9]. In this article, we present a compact cold atom gravimeter dedicated to field applications. First, we describe our apparatus and the technologies that we use to have a compact and reliable instrument. Then, we present the performances of the gravimeter in a laboratory environment. Finally, we report gravity measurements in a static and in a moving elevator.

The principle of our cold atom gravimeter is well described in the literature [1] and we summarize in this letter only the basic elements. In an atom gravimeter, the test mass is a gas of cold atoms which is obtained by laser cooling and trapping techniques [10]. This cloud of cold atoms is released from the trap and its acceleration is measured by an atom interferometry technique. We use a Mach-Zehnder type atom interferometer consisting in a sequence of three equally spaced Raman laser pulses which drive stimulated Raman transitions between two stable states of the atoms. In the end, the proportion of atoms in the two stable states depends sinusoidally on

the phase of the interferometer φ which is proportional to the acceleration g of the atoms along the Raman laser direction of propagation:

$$\varphi = k_{\text{eff}} g T^2, \quad (1)$$

where $k_{\text{eff}} \simeq 4\pi/\lambda$ is the effective wave vector associated to the Raman transition, λ is the laser wavelength and T is the time between the Raman laser pulses.

The description of our gravimeter setup is the following. The cold atoms are produced and fall in a vacuum chamber made of glass connected to a titanium part to which are connected a 3 l/s ion pump, getters and rubidium dispensers. This vacuum chamber is inside a magnetic shield consisting of 4 layers of mu-metal. The falling distance of the atoms is equal to 6 cm. The sensor head containing the vacuum chamber, the magnetic shield, the magnetic coils and the optics for shaping the laser beams and collecting the fluorescence has a height of 40 cm and a diameter of 33 cm. The gravimeter is placed onto a passive vibration isolation table (Minus-K). The laser system for addressing ^{87}Rb atoms is similar to the one described in reference [11]. Basically, a distributed feedback (DFB) laser diode at $1.5 \mu\text{m}$ is amplified in a 5 W erbium doped fiber amplifier (EDFA) and then frequency doubled in a periodically poled lithium niobate (PPLN) crystal. A power of 1 W at 780 nm is available. The frequency of the laser is controlled thanks to a beatnote with a reference laser locked on a Rubidium transition. The Raman laser and the repumper are generated with a fiber phase modulator at $1.5 \mu\text{m}$ which generates side bands at 7 GHz. All the electronics and the optics of the gravimeter fit in one 19" rack ($0.6 \times 0.7 \times 1.9 \text{ m}$).

The experimental sequence of the gravimeter consists in the following. First, ^{87}Rb atoms are loaded from a background vapor in a 3D magneto-optical trap. The atoms are then further cooled down in an optical molasses to a temperature of $1.8 \mu\text{K}$. Then, the atoms are selected in the state $F = 1, m_F = 0$ thanks to a microwave selection. After 10 ms of free fall, we apply the atom interferometer sequence consisting in three Raman laser pulses of duration 10, 20 and 10 μs . The Raman laser pulses couple the state $F = 1, m_F = 0$ to the state $F = 2, m_F = 0$. The time between the Raman pulses is equal to $T = 48 \text{ ms}$. During the interferometer sequence, a vertical uniform magnetic field of 28 mG is applied.

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A radio frequency chirp of $\alpha/2\pi \sim 25.1\text{MHz/s}$ is also applied to the Raman frequency in order to compensate the time-dependant Doppler shift induced by gravity. Finally, the proportion of atoms in the state $F=2$ and $F=1$ is measured by collecting the fluorescence of the atoms illuminated with three pulses of a vertical retro-reflected beam of durations of 2, 0.1, and 2 ms. The first and the last pulses resonant with the $F = 2 \rightarrow F' = 3$ transition give a fluorescence signal proportional to the number of atoms in the state $F=2$ and the middle pulse resonant with $F = 1 \rightarrow F' = 2$ transition transfers the atoms from the state $F=1$ to the state $F=2$. A rms noise of 0.2% on the measured proportion of atoms is obtained with this detection scheme limited by the frequency noise of the laser. The repetition rate of the experimental sequence is equal to 4 Hz. The measurement of the proportion of atoms P in the state $F = 2$ versus the radio frequency chirp α leads to interference fringes given by the formula:

$$P = P_m - \frac{C}{2} \cos((k_{\text{eff}} g - \alpha)T^2), \quad (2)$$

where P_m is the mean proportion of atoms in the state $F = 2$, C is the contrast which is equal in our case to $C = 0.36$.

The protocol of the gravity measurements is the following. The gravity is measured by acquiring P from each side of the central fringe i.e. for $\alpha \simeq k_{\text{eff}} g \pm \pi/2T^2$. The sign of α and thus the sign of k_{eff} is also changed every two drops in order to eliminate systematic effects which change of sign with k_{eff} . In order to follow slow variations of gravity, the central value of α is also numerically locked to the central fringe. For each atom drop, the gravity is determined with the last 4 measurements using the following relations :

$$\begin{aligned} \alpha_n &= s \left(\alpha_n^0 + (-1)^n \frac{\pi}{2T^2} \right) \\ g_n &= \sum_{i=0}^3 \frac{\alpha_{n-i}^0}{4|k_{\text{eff}}|} - \frac{1}{|k_{\text{eff}}|T^2} \arcsin \left(\sum_{i=0}^3 \frac{(-1)^{n-i} P_{n-i}}{2C} \right) \\ \alpha_{n+1}^0 &= \alpha_n^0 - G(\alpha_n^0 - |k_{\text{eff}}|g_n) \end{aligned} \quad (3)$$

where α_n is the radio frequency chirp applied at the n -th drop of the atoms, α_n^0 is the value of the central fringe used at the n -th drop of the atoms, $s = \pm 1$ is the sign of radiofrequency chirp which changes every two drops, P_n is the proportion of atoms in the state $F=2$ measured at the n -th drop, g_n is the gravity measurement at the n -th drop and G is the gain of the lock of the central value of α .

The gravimeter was tested in our laboratory by acquiring continuously gravity during five days. The measurements averaged over 15 minutes are shown on Fig. 1. A good agreement is obtained with our tide model [12] with a rms difference of $7 \mu\text{Gal}$. The Allan standard deviation on the gravity measurements corrected for the tides is shown on Fig. 2. A short term sensitivity of $65 \mu\text{Gal}/\text{Hz}^{1/2}$ is obtained during the five days of gravity measurements. During the night, when the level

of vibration is lower, one gets a better sensitivity of $42 \mu\text{Gal}/\text{Hz}^{1/2}$.

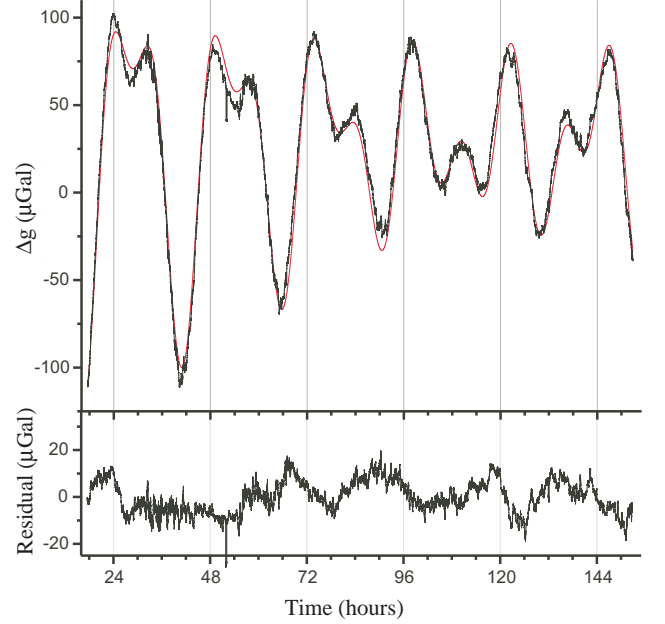


FIG. 1. Continuous gravity measurements from 27 May to 2 June 2009. The data are averaged over 15 minutes (3600 atom drops). Top: gravity measurements uncorrected from tides with the tide model in red solid line. Bottom: residual between the gravity measurements and the tide model.

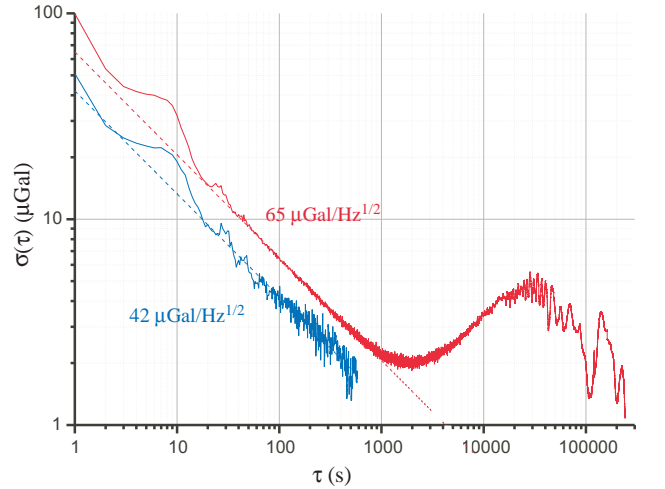


FIG. 2. Allan standard deviation of the gravity measurements. The top red line corresponds to the Allan standard deviation of data taken during five days. The bottom blue line corresponds to data taken during one night when the vibration level is lower.

This difference of sensitivity between night and day

indicates that the sensitivity of the gravimeter is limited by the vibrations. This is confirmed by our estimation of the other sources of noise. The detection noise limits the sensitivity at $15 \mu\text{Gal}/\text{Hz}^{1/2}$. The phase noise of our microwave source limits the sensitivity at $2 \mu\text{Gal}/\text{Hz}^{1/2}$. The frequency noise of the Raman laser [13] limits the sensitivity at $\sim 1 \mu\text{Gal}/\text{Hz}^{1/2}$.

The main systematic effects which limit the accuracy of the gravimeter were evaluated and are listed in Table I. Our method of generating the Raman laser by modulation induces a systematic error on the gravity measurement. This effect was studied in detail in reference [14]. In our case, one obtains an uncertainty of $8 \mu\text{Gal}$. The systematic effects caused by the inhomogeneity of the magnetic field [1] and the first order light shift [1] change of sign with k_{eff} . These effects cancel therefore with our protocol of measurement consisting in alternating the sign of k_{eff} . The residue of these effects is estimated to be below $1 \mu\text{Gal}$ and is negligible compared to the other systematic effects. The second order light shift [15, 16] has been calibrated by measuring gravity versus the power of the Raman laser. Our uncertainty on the calibration is equal to $2 \mu\text{Gal}$. The Coriolis effect gives an error equal to $2 v_t \Omega$ where Ω is the rotation rate of the earth projected in the horizontal plane and v_t is the transverse velocity of the atoms perpendicular to the Earth rotation vector. The uncertainty on the transverse velocity of the atoms detected is estimated in our case at 2 mm/s leading to an uncertainty on g equal to $19 \mu\text{Gal}$. The wavefront curvature of the Raman laser caused by imperfect optics is causing an error equal to σ_v^2/R [3] where σ_v is the rms width of the velocity distribution of the atoms and R is the radius of curvature of the wavefront. We estimate that our optics induce a wavefront curvature with a radius $|R|$ around 1.4 km leading to an uncertainty of $12 \mu\text{Gal}$. The Raman laser is aligned vertically by maximizing the value of gravity. This procedure leads to an uncertainty of $2 \mu\text{Gal}$. The uncertainty on our laser wavelength is equal to 2 MHz giving an uncertainty of $5 \mu\text{Gal}$. The quadratic sum of all these contributions gives a total uncertainty of $25 \mu\text{Gal}$. This accuracy estimation of our gravimeter has been confirmed by the comparison with a relative gravimeter (Scintrex CG-5) calibrated with an absolute gravimeter. The relative gravimeter gives a measurement of gravity equal to $980883499 \pm 6 \mu\text{Gal}$. Our atom gravimeter gives $980883165 \pm 25 \mu\text{Gal}$. The difference of height between the two gravimeters is equal to $1.09 \pm 0.03 \text{ m}$ leading to a correction due to vertical gravity gradient of $347 \pm 10 \mu\text{Gal}$. Finally, one obtains a difference between the two measurements equal to $13 \pm 28 \mu\text{Gal}$ in agreement with the error bar.

The gravimeter was tested in an elevator located in a 14 levels building. A gravity measurement was done at each level with an acquisition time of 250 s (1000 drops). The distance between the levels was measured with a laser distance measurer pointing the top of the elevator cage. At each level, the verticality of the gravimeter was

Effect	Bias (μGal)	Uncertainty (μGal)
Raman laser generated by modulation	-18	8
Light shift second order	43	2
Coriolis effect	0	19
Wavefront curvature	0	12
Verticality	0	2
Laser wavelength	0	5
Total	25	25

TABLE I. Main systematic effects on the gravity measurements.

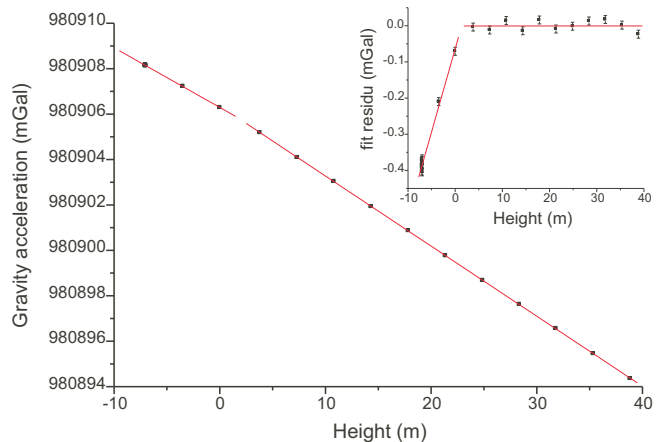


FIG. 3. Gravity measurements versus height in an elevator. The points are the experimental measurements. The lines are a linear fit of the measurements overground and underground. The inset in the up right corner is the difference between the measurements and the overground linear fit and shows clearly the two slopes which correspond to the gravity gradient overground and underground.

set thanks to an inclinometer. Between each gravity measurement at a given level, a gravity measurement at the level -2 was done in order to check for the repeatability of gravity measurements. The gravity measurements at the level -2 have a standard deviation of $11 \mu\text{Gal}$. The gravity measurements at each level are plotted on the Fig. 3. One can see that the gravity gradient is different above the floor and under the floor. Overground, a linear fit of the data gives a gravity gradient equal to $3086 \pm 4 \text{ E}$. This value agrees with the mean gravity gradient on the Earth (free-air anomaly) given in the literature [17]. Underground, a linear fit of the data gives a gravity gradient equal to $2626 \pm 16 \text{ E}$. The lower underground gravity gradient is due to the mass of the soil above the measurement point which gives a correction equal to $4\pi\rho G$ where ρ is the density of the soil.

In order to demonstrate the possibility to measure gravity in a boat or a plane with an atom gravimeter, we measured gravity while the elevator was moving. To perform this measurement, our vibration isolation table which can not work while the elevator is moving was

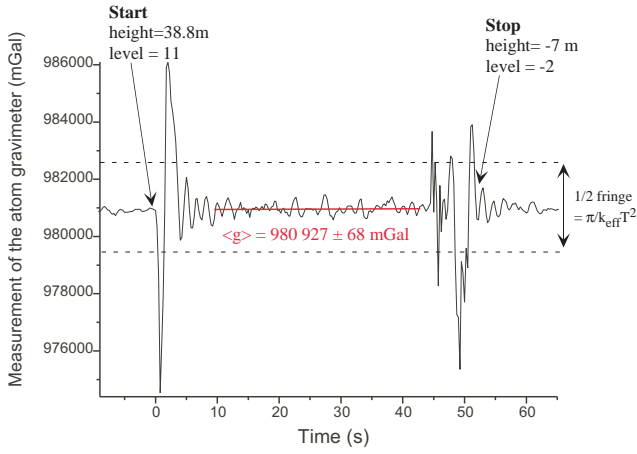


FIG. 4. Gravity measurements in a moving elevator. The red line corresponds to the averaged value of the gravity measured during the stabilized part of the descent of the elevator.

blocked. Thus, the time of the interferometer T was reduced from 48 ms to 1 ms in order to have variations of acceleration smaller than one fringe. The measurements of the gravimeter acquired when the elevator was moving from the level 11 to the level -2 are shown on Fig. 4. By assuming that the mean acceleration of the elevator is null during the stabilized part of the descent of the elevator (10 s - 43 s), the measurements in dynamic

give a measurement of gravity equal to 980927 ± 68 mGal which agrees with the static measurements. The statistical uncertainty of 68 mGal comes from the acceleration variations of the elevator and the vibrations.

In conclusion, we demonstrated the possibility to perform quantitative gravity measurements in a non-laboratory environment with an atom gravimeter. This demonstration was possible with the development of a compact and robust atom gravimeter. Despite the fact that we chose a small falling distance in order to have a compact apparatus, we obtain performances (sensitivity $42 \mu\text{Gal}/Hz^{1/2}$ and accuracy $25 \mu\text{Gal}$) close to the best gravimeters. Quantitative gravity measurements with a repeatability of $11 \mu\text{Gal}$ were performed in an elevator wherein the apparatus is subject to shocks, vibrations and fluctuations of temperature. These measurements led us to the determination of the gravity gradient with a precision of 4 E. We also demonstrated the ability of an atom gravimeter to be used in a mobile platform by measuring gravity in a moving elevator. Finally, we point out that technological developments concerning the vibration isolation system or the association with a classical accelerometer [8, 18] have still to be made in order to have quantitative gravity measurements in mobile platforms.

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